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BREAKING KELVIN-HELMHOLTZ WAVES AND CLOUD-TOP ENTRAINMENT AS REVEALED BY K-BAND DOPPLER RADAR

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1. INTRODUCTION

Radars have occasionally detected breaking Kelvin-Helmholtz (KH) waves under clear-air conditions in the atmospheric boundary layer (e.g. Gossard et al. 1970) and in the free troposphere (e.g. Browning 1971). However, very few direct measurements of such waves within clouds have previously been reported (Takahashi et al. 1992; Weckwerth and Wakimoto 1992), and those have not clearly documented wave breaking. In this article we present some of the most detailed and striking radar observations to date of breaking KH waves within clouds and at cloud top and discuss their relevance to the issue of cloud-top entrainment, which is believed to be important in convective (Reuter 1986) and stratiform clouds. Aircraft observations reported by Stith (1992) suggest that vortex-like circulations near cloud top are an entrainment mechanism in cumuliform clouds. Laboratory and modeling studies (Broadwell and Breidenthal 1982; Baker et al. 1984) have examined the possibility that KH instability may be responsible for mixing at cloud top, but direct observations have not yet been presented. Preliminary analyses shown here may help fill this gap.

The data presented in this paper were obtained during two field projects in 1991 that included observations from the NOAA Wave Propagation Laboratory's K_a-band Doppler radar (wavelength = 8.7 mm) and special rawinsonde ascents. The sensitivity (-30 dBZ at 10 km range), fine spatial resolution (37.5-m pulse length and 0.5° beamwidth), velocity measurement precision (5-10 cm s^{-1}), scanning capability, and relative immunity to ground clutter make it sensitive to non-precipitating and weakly precipitating clouds (Martner and Kropfli 1993), and make it an excellent instrument to study gravity waves in clouds. In particular, the narrow beam width and short pulse length create scattering volumes that are cylinders 37.5 m long and 45 m (90 m) in diameter at 5 km (10 km) range. These characteristics allow the radar to resolve the detailed structure in breaking KH waves such as have been seen in photographic cloud images (e.g. Martner 1985).

2. KH BILLOWS IN A NON-PRECIPITATING STRATIFORM CLOUD

As part of the Winter Icing and Storms Project (WISP) in early 1991, the K-band radar was operating at Erie, Colorado (1503 m above mean sea level) during the approach and passage of a strong and complex cold front. The mode of operation consisted of making east-west oriented range-height indicator (RHI) scans every 15 min. At 0500 UTC 6 March, several hours after the passage of the surface cold front, a relatively unperturbed layer of stratiform clouds was present over the radar from 2-6 km above ground level (AGL). (Henceforth altitudes will be AGL, unless otherwise stated.) However, by 0600 UTC the reflectivity pattern of the cloud layer had taken on the structure of KH billows (Fig. 1a). Comparison of the radar data with a CLASS rawinsonde ascent launched at the same time from Platteville, 27 km east of the radar, shows that the billows were located in a layer of strong vertical wind shear, but below the layer of strongest shear within the upper front (Fig. 1b). The Richardson number (Ri) profile (Fig. 1c), calculated from the rawinsonde data, also indicates that the billows were in a deep layer of low Ri in which KH instability could occur.

Further verification that the observed reflectivity pattern is a manifestation of breaking KH waves can be gained by comparing the wave parameters with well-known features of KH waves. While several of the important wave characteristics can be determined directly from the radar observations, others require calculations based on theoretical considerations. In this case study, an upper bound for the horizontal wavelength (λ) can be determined directly from the RHI of reflectivity (Fig. 1a), and is 6.1 km. From the observed reflectivity patterns at 0545 (not shown) and 0600 UTC, it is possible to track the easternmost billow cloud, yielding a zonal phase speed of 15 m s^{-1}. However, in order to determine the actual λ it is also necessary to know the wave orientation, or the ground-relative horizontal phase velocity (c). Because only east-west RHI's were performed, c must be estimated from the shear across the layer containing the wave (layer method), or from the wind velocity at the wave's critical level (center method), which is at the center of the billow. In the layer method, the propagation direction is given by the direction of the shear vector and the phase speed is given by the component of the layer mean flow in that direction. Two logical choices for the shear layer are evident in this case: 1) the layer between 2.0 and 5.8 km which contains all of the cloud, and most of the shear below the upper front, and 2) the layer between 2.7 and 4.9 km that marks the vertical range of the billow structure. These predict values of c that are 15.4 m s^{-1} from 232°, and 11.6 m s^{-1} from 222°, respectively. The center method predicts that c is 20 m s^{-1} from 272° as an average from 3.5-4.2 km, but it is very sensitive to the choice of critical level because of the strong

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directional shear and speed shear in that layer (i.e., from 16-26 m s^{-1} and 280-266°). Thus, λ appears to be 5.1 ± 1.0 km, with c = 15.8 ± 4.2 m s^{-1} from 247 ± 25°. Hence, the zonal component of c calculated from theoretical considerations is 14.8 ± 4.1 m s^{-1}, which compares favorably with the observed value.

Another important wave parameter is the ratio between λ and the shear layer depth (H). Taking the vertical extent of the billow structure (i.e., 2.7-4.9 km) as the most appropriate shear layer yields H=2.2 km. Thus, the ratio λ/H=2.3±0.5 is somewhat less than the value of 3.2-3.5 observed in the atmospheric boundary layer (Gossard et al. 1970, and Hooke et al. 1973). It is also smaller than the ratios predicted for the fastest growing mode of KH instability by Drazin (1958) for a continuous model (λ/H=4.4), by Miles and Howard (1964) for a piecewise 3-layer model (λ/H=7.5), and by Holmboe (see Gossard 1990) for an alternate continuous model (λ/H=3-6, depending on Ri).

3. KH BILLOWS ATOP A DEEP, PRECIPITATING CLOUD

During November 1991 the radar was deployed in Coffeyville, Kansas (227 m MSL) as part of the FIRE-II experiment and was co-located with a rawinsonde launch site. As a weak cyclone deepened to the south of the radar site on 22 November, a frontal zone developed in the lower troposphere and helped trigger deep stratiform rain clouds. By 1800 UTC the cloud filled the layer between 2 and 8 km and produced light rain that can be seen as fall streaks extending from cloud base to the ground (Fig. 2). The radar operated in the vertically-pointing mode during this event. The waves occurred at the top of the cloud, and had the distinctive structure of KH billows as revealed in the radial velocity plot (Fig. 3a) which focuses on the time and region of interest. This plot also displays the remarkable spatial resolution of the radar, and its ability to clearly measure the wave activity. The time series of vertical velocity near the center of the billows (Fig. 3b) allows a more quantitative assessment of the waves. This data indicates the wave had a period of 68 ± 4 s and a maximum amplitude of 1.7 m s^{-1}. Although these measured Doppler velocities are actually a combination of the clear-air vertical motion and the hydrometeor fall speed, the terminal velocities are likely to be < 0.1 m s^{-1} since the region is at cloud top and the reflectivities are small (-20 dBZ), i.e., the hydrometeors are small. This conclusion is supported by the fact that the amplitude of the upward motion (1.7 m s^{-1}) is only 0.1 m s^{-1} less than that of the downward motion (-1.8 m s^{-1}).

Figure 4 shows the radial velocity in the upper half of the cloud (Fig. 4a) and the temperature and wind speed profiles (Fig. 4b) from a rawinsonde that ascended through the layer containing the waves. The rawinsonde reached the appropriate altitude 25-35 min before the waves appeared over the radar, and had drifted 25-30 km to the northeast. The waves developed in a layer of strong vertical shear (primarily speed shear) between 7.5 and 8.5

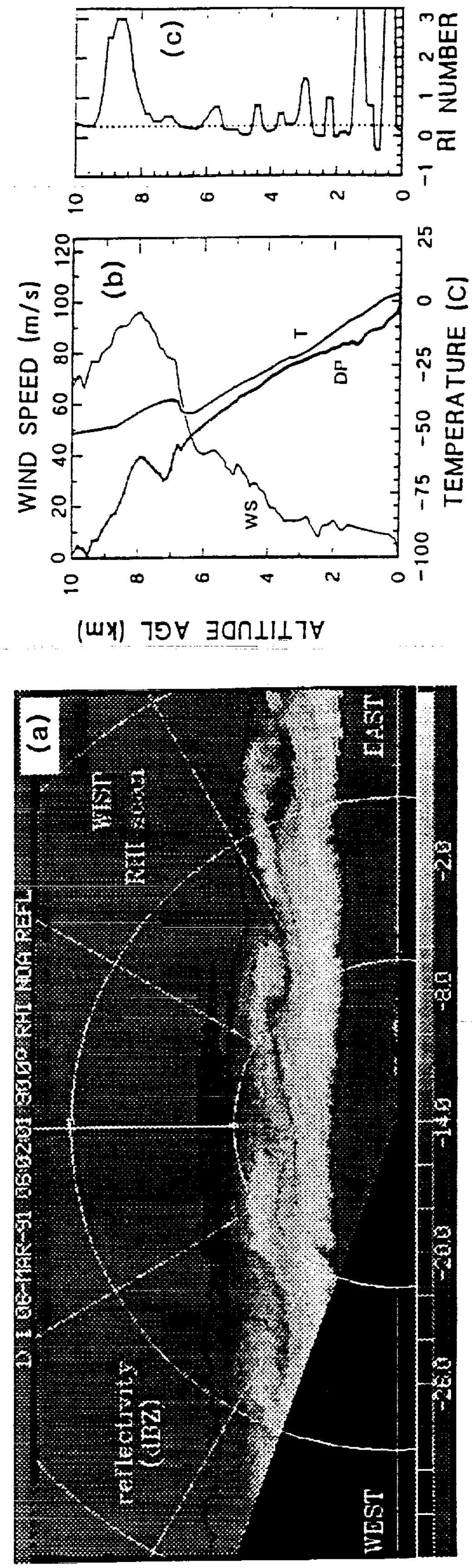

Fig. 1 a) RHI of radar reflectivity at 0600 UTC. b) Temperature, dew point temperature, and wind speed from a CLASS sounding at Platteville at 0600 UTC. c) Richardson number calculated from the sounding in (b).

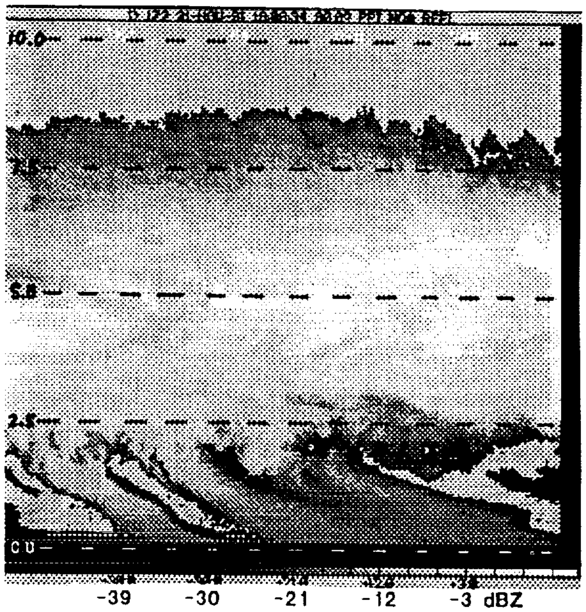

Fig. 2 Time-height cross section of radar reflectivity. Horizontal axis spans 14.5 minutes.

km that had Ri ≈ 0.25 (Fig. 4c).

As with the earlier case, it is possible to estimate λ and c from the conditions in the shear layer. In this case the wave period is also known, but there is no measurement to provide an upper bound on λ. Two plausible options for the shear layer are the layer from 7.3-8.3 km that contains most of the vertical shear, and the layer from 7.5-8.55 km that defines the vertical extent of the billow clouds. These yield values of 35.9 m s^{-1} from 209°, and 38.6 m s^{-1} from 220°, respectively. The alternative method that uses the wind vector at the center altitude of the billows yields 33.0 m s^{-1} from 229°, or 38.0 m s^{-1} from 226°, for altitudes of 7.6 and 8.0 km, respectively. Thus, c is 35.8 ± 2.8 m s^{-1} from 219 ± 10°. Combining this result with the observed wave period predicts λ = 2.4 ± 0.3 km. Taking the depth of the layer of low Ri (i.e., 650-930 m) as H yields a ratio of λ/H=3.0 ± 1.0. Based on the observed wave structure, conditions in the wave environment, and the deduced wave parameters, it is possible to conclude that the observed perturbations at cloud top are the result of KH instability.

4. RELATIONSHIP TO CLOUD-TOP ENTRAINMENT

The observations presented here provide convincing evidence that KH instability can mix relatively clear air (i.e., containing few if any hydrometeors at < -30 dBZ) at least 1-2 km down into stratiform clouds (Figs. 1a and 4a). In one case the mixing includes roughly half of the vertical extent of a 4-km deep nonprecipitating cloud, while in another case the waves developed along the top of a 6-km deep cloud and produced distinct vertical motion perturbations that extended fully 2 km below cloud top (Fig. 4a). Although the waves created large vertical displacements (at least 1 km) and mixed apparently unsaturated and saturated air, it does not appear that they triggered strong downdrafts in these clouds. This may be due in part to the stratiform nature of the clouds, which implies that the formation of downdrafts would be inhibited. Vigorous downdrafts are more likely to develop under less stable conditions.

Attention has also focused on cloud-top entrainment as a possible mechanism for the breakup of marine stratocumulus (e.g. Siems and Bretherton 1992). As with the problem of entrainment in cumuliform clouds, the exact mechanism that is active in stratiform clouds has not yet been clearly documented observationally. Because the cases shown here are primarily stratiform in nature they provide evidence that may be relevant to this issue, although it is desirable to obtain similar radar observations in shallow marine stratocumulus.

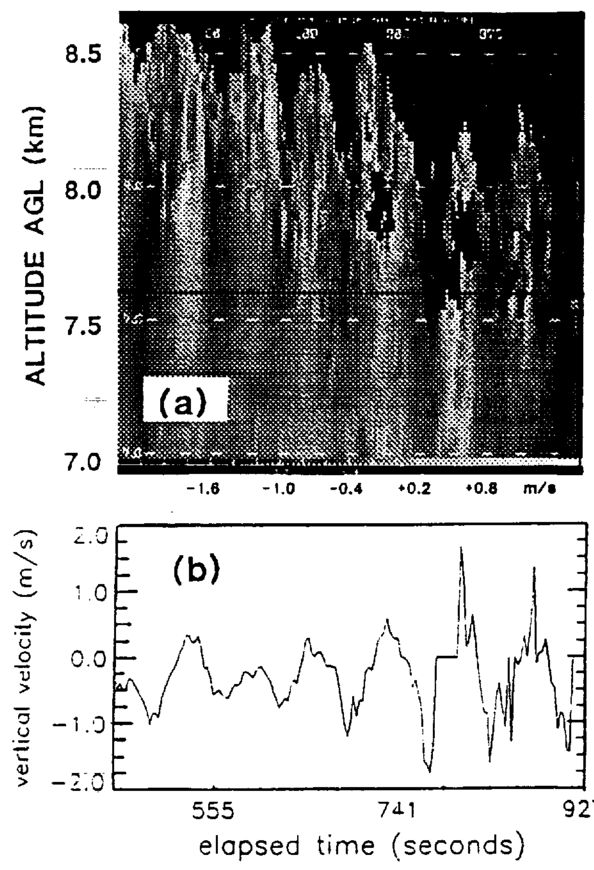

Fig. 3 a) Time-height cross-section of Doppler vertical velocity centered on the KH billows seen atop the cloud in Fig. 2. Regions where reflectivity is < -35 dBZ are shown as black. b) Time-series of Doppler vertical velocity at height shown as a black line in (a).

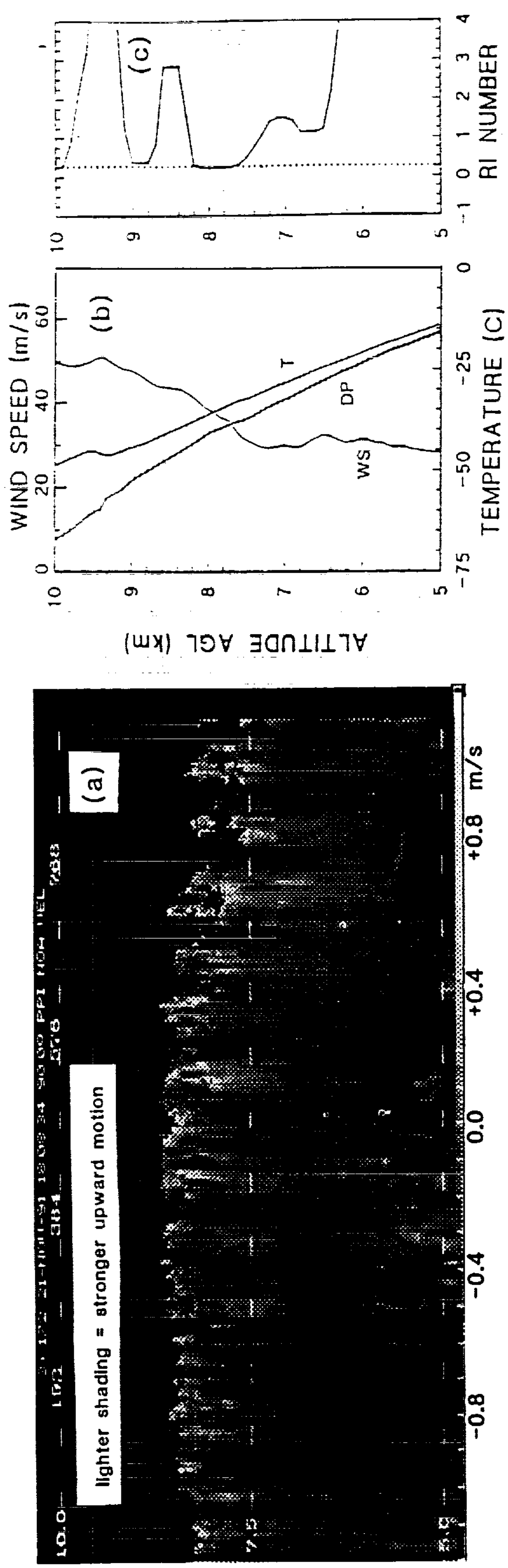

Fig. 4 a) Time-height cross section of Doppler vertical velocity in the upper half of the cloud shown in Fig. 2. b) and c) Same as Fig. 1, but from Coffeyville, KS at 1711 UTC.

5. ACKNOWLEDGEMENTS

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